All binary black holes may form dynamically: The eccentric perspective

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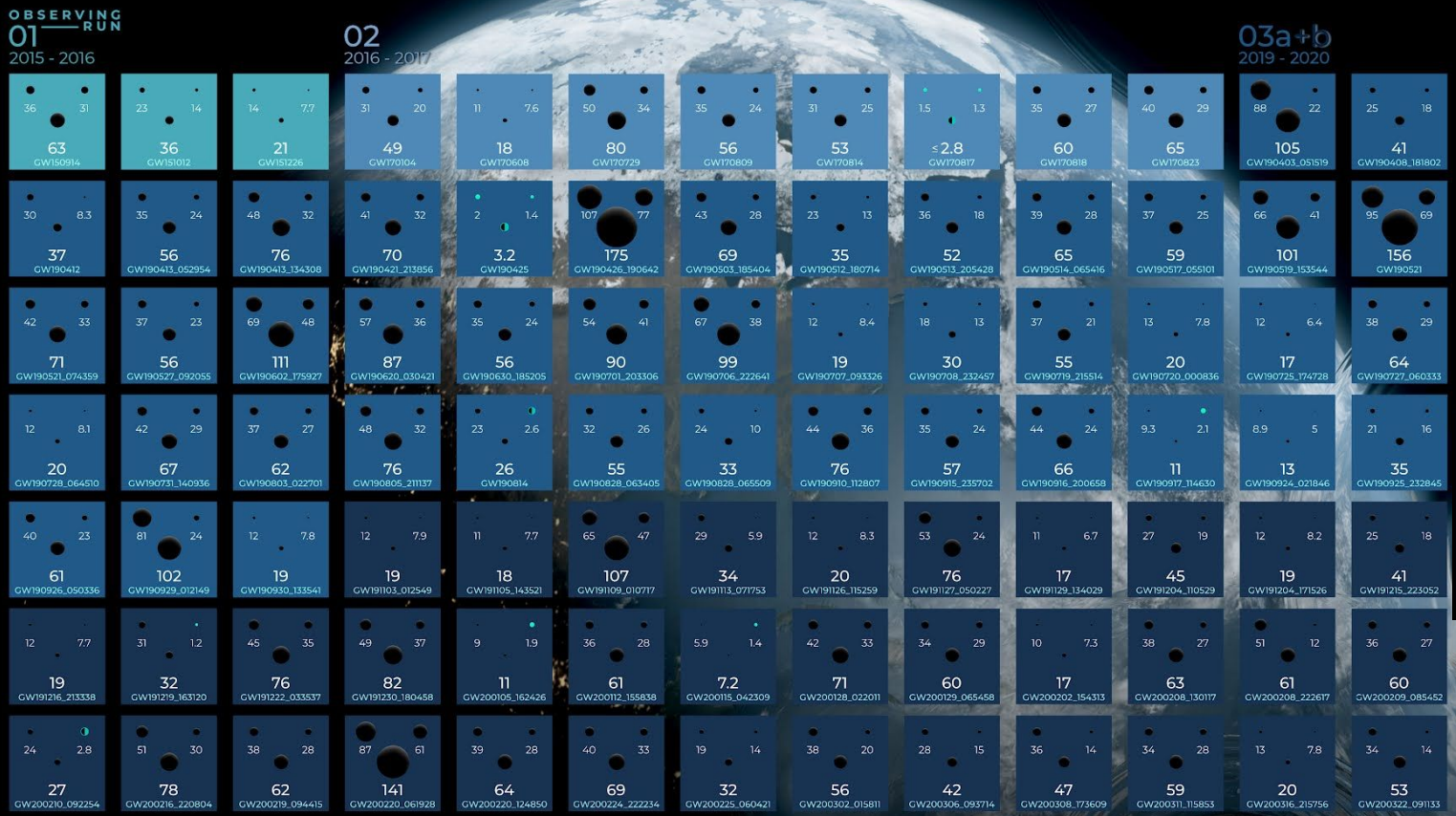
NBIA Workshop on Black Hole Dynamics
31.05.22

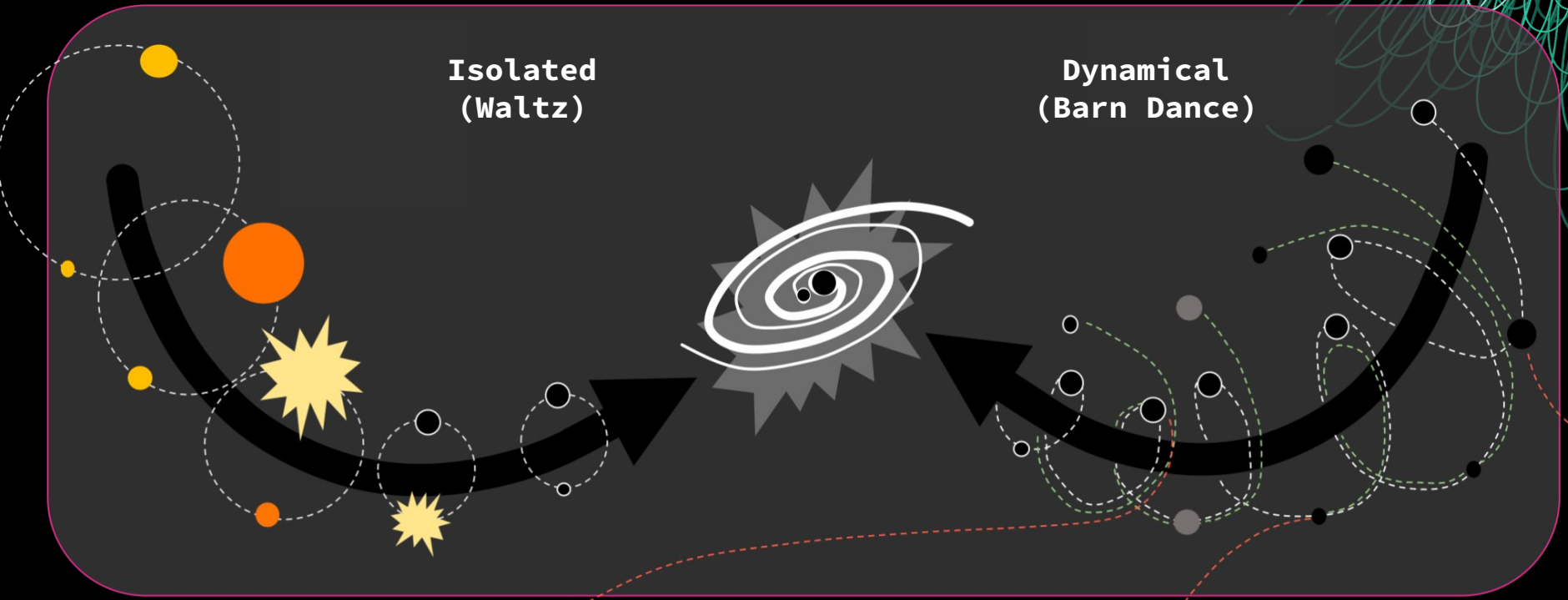
LIGO OzGrav MONASH University

Gravitational Waves Detected: 2015-2020



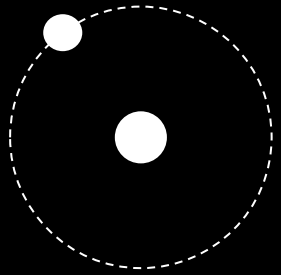
O2Grav

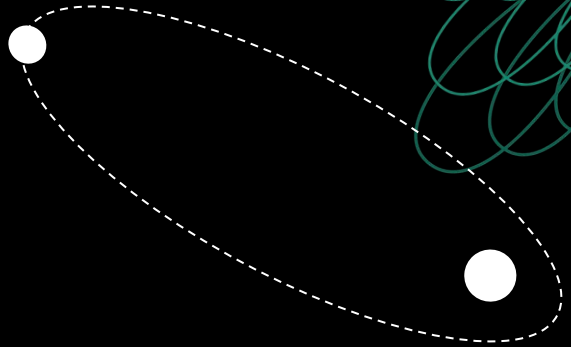
Formation channels

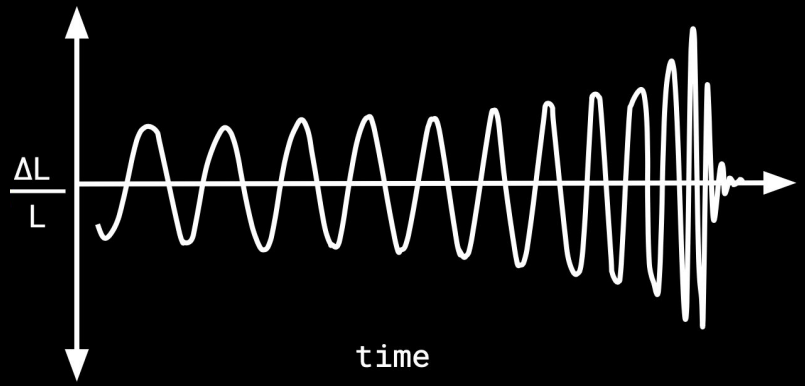


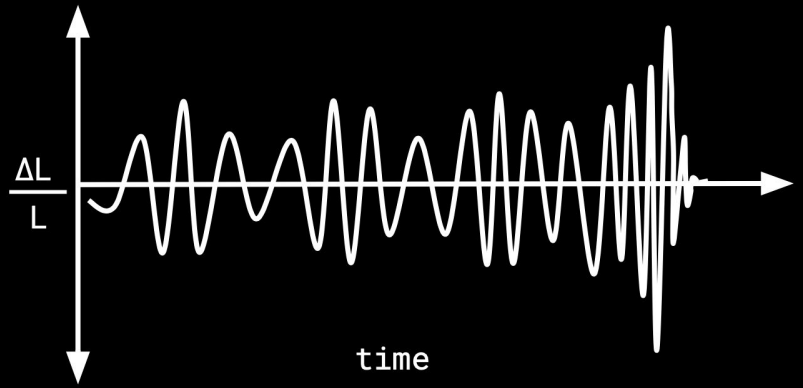
Distinguishing features of formation channels

- **Mass, Spin, Eccentricity**



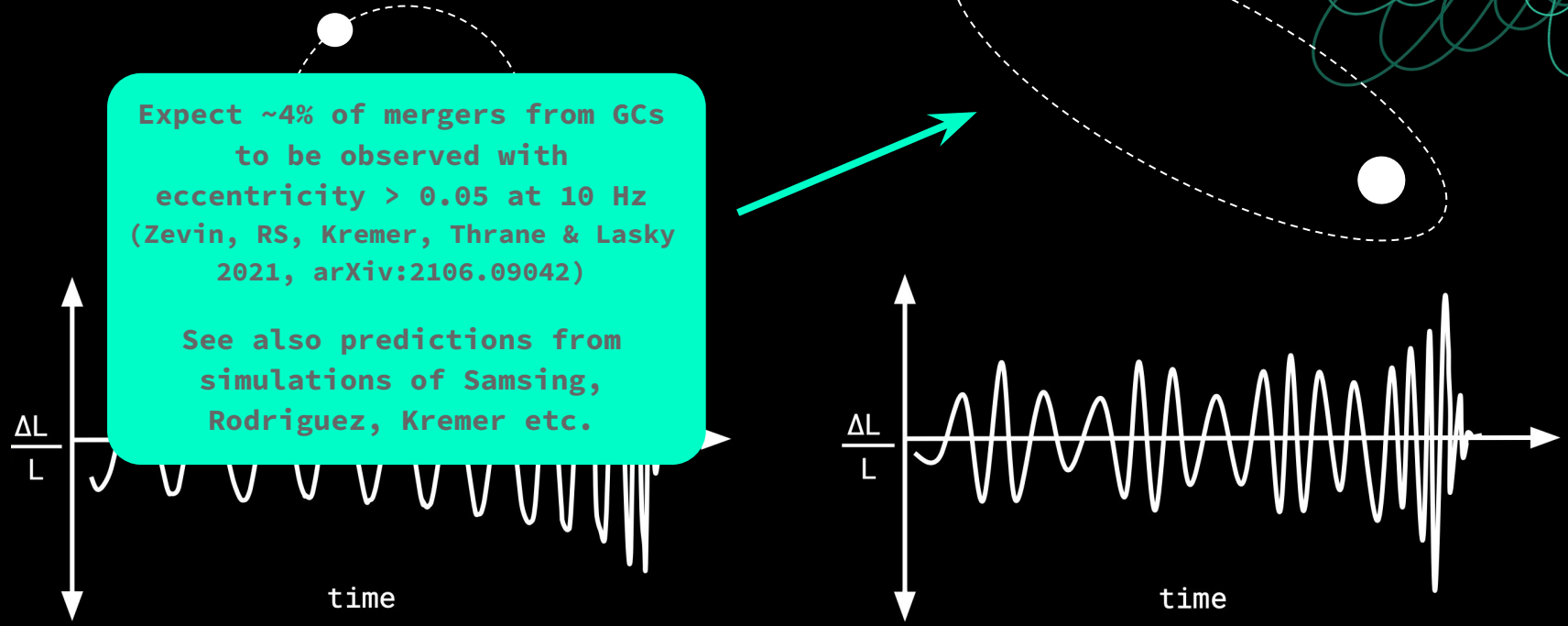






Distinguishing features of formation channels

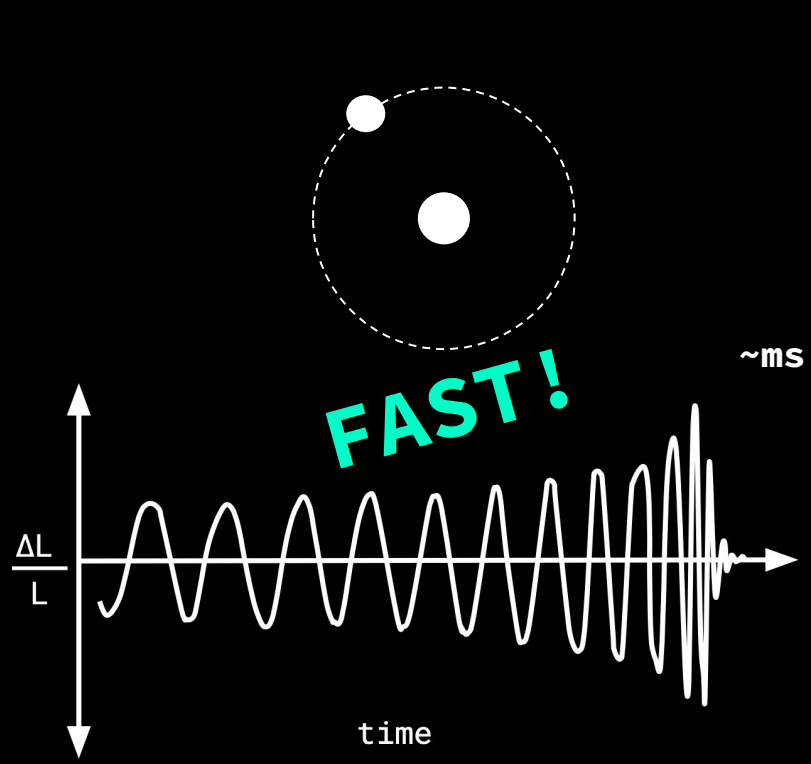
- **Mass, Spin, Eccentricity**

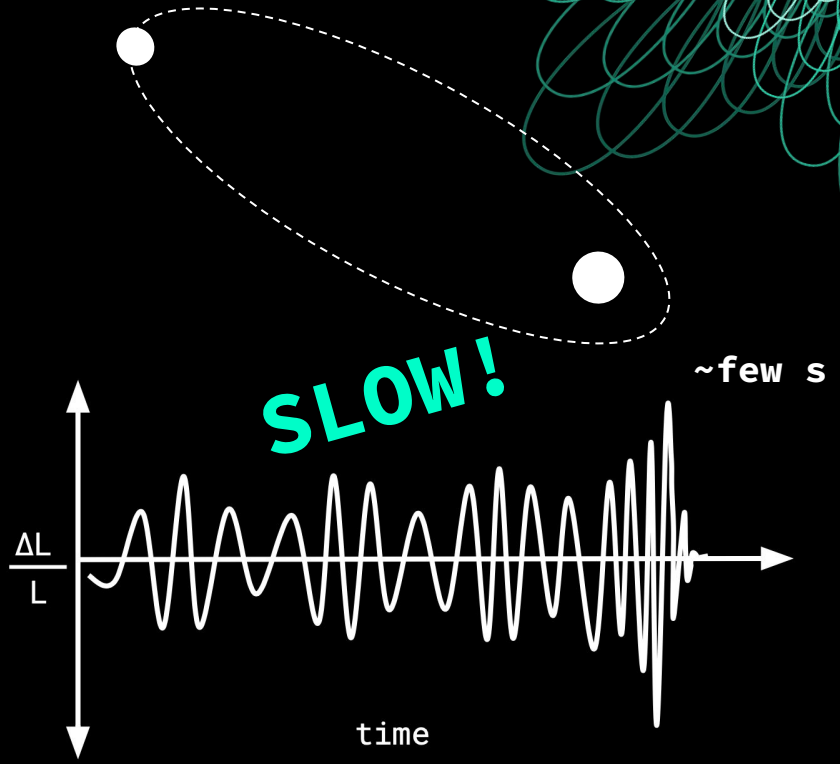


Expect ~4% of mergers from GCs to be observed with eccentricity > 0.05 at 10 Hz (Zevin, RS, Kremer, Thrane & Lasky 2021, arXiv:2106.09042)

See also predictions from simulations of Samsing, Rodriguez, Kremer etc.

Problem: Eccentric waveforms are slow





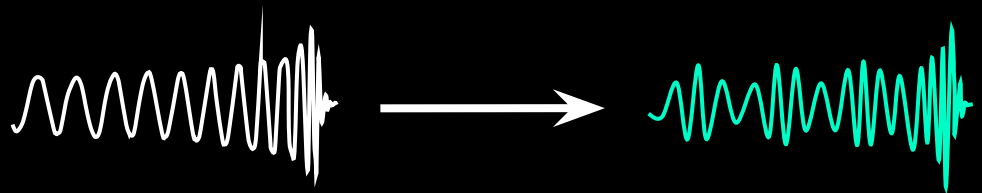
Possible Solutions

- **Likelihood reweighting**
  - **SEOBNRE**; as demonstrated by RS, Lasky & Thrane 2019, arXiv:1909.05466, RS, Farrow, Stevenson, Thrane & Zhu 2020, arXiv:2001.06492, RS, Lasky, Thrane & Calderon Bustillo 2020, arXiv:2009.04771, RS, Lasky & Thrane 2021, arXiv:2108.01284
  - See also Payne, Talbot & Thrane 2019, arXiv:1905.05477

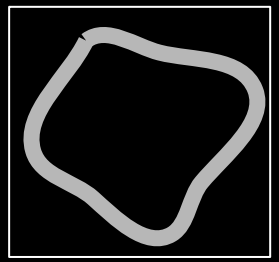
- **Use faster inspiral-only waveform**
  - **TaylorF2Ecc**; as demonstrated by Lower, Lasky & Thrane 2019, arXiv:1806.05350; Lenon et al. 2020, arXiv:2005.14146

- **Adjust error threshold of ODE solver within code**
  - **TEOBResumSe**; as demonstrated by O'Shea & Kumar 2021, arXiv:2107.07981

Solution: Likelihood reweighting



Proposal



Target

Ashton et al. 2019, arXiv:1811.02042

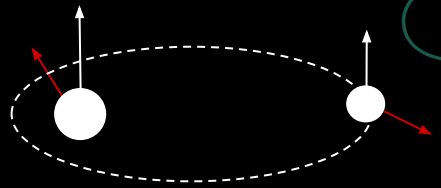
RS et al. 2020c, arXiv:2006.00714

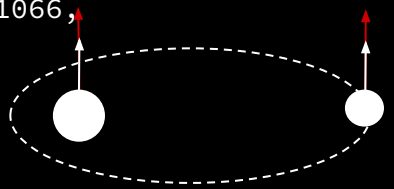
marginalised over eccentricity

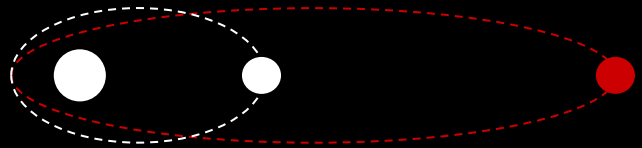
$$P(\theta|d) = \frac{L(d|\theta)\,\pi(\theta)}{Z(d)} \longrightarrow P(\theta|d)_e = \frac{L(d|\theta)_e}{L(d|\theta)}\,P(\theta|d)$$

then reconstruct eccentricity distribution from marginal 1D likelihood (ask me for the bonus slide!)

Caveats







- **Spin-precession or eccentricity?**
  - Can be confused for each other
  - See Calderón-Bustillo et al. 2020, arXiv:2009:01066, Romero-Shaw et al. 2020b, arXiv:2009.04771
- **Aligned spin magnitude capped at 0.6**
- **Eccentricity magnitude capped at 0.2 (10 Hz)**
- **Initial argument of periapsis is fixed**
  - Don’t think this affects results significantly - see Teagan Clarke’s upcoming work
- **“Eccentricity” has no consistent definition between simulations / models**
  - Measurements not directly comparable to model predictions / measurements using other models
  - See Alan Knee’s upcoming work

Blind spots

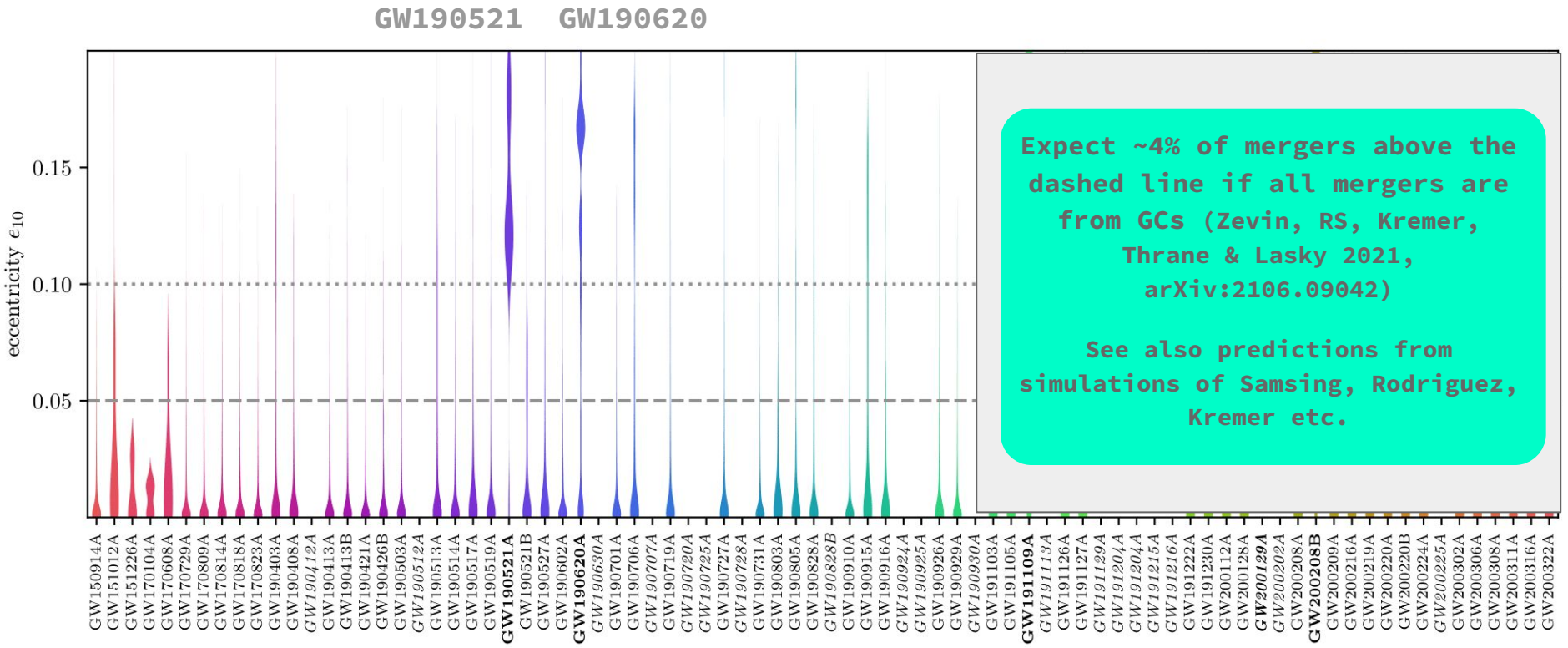
- **We neglect events that may contain neutron stars**
  - Leaves us with 82 **confident** BBH

- **We neglect events that wind up undersampled**
  - Leaves us with 62 **well-sampled** confident BBH

$$w_i = \frac{L(d|\theta_i)e}{L(d|\theta_i)} \qquad n_{eff} = \frac{\text{sum}(w_i)\ **\ 2}{\text{sum}(w_i\ **\ 2)}$$

WARNING: Next slide has white background!

Results: GWTC-1 and GWTC-2

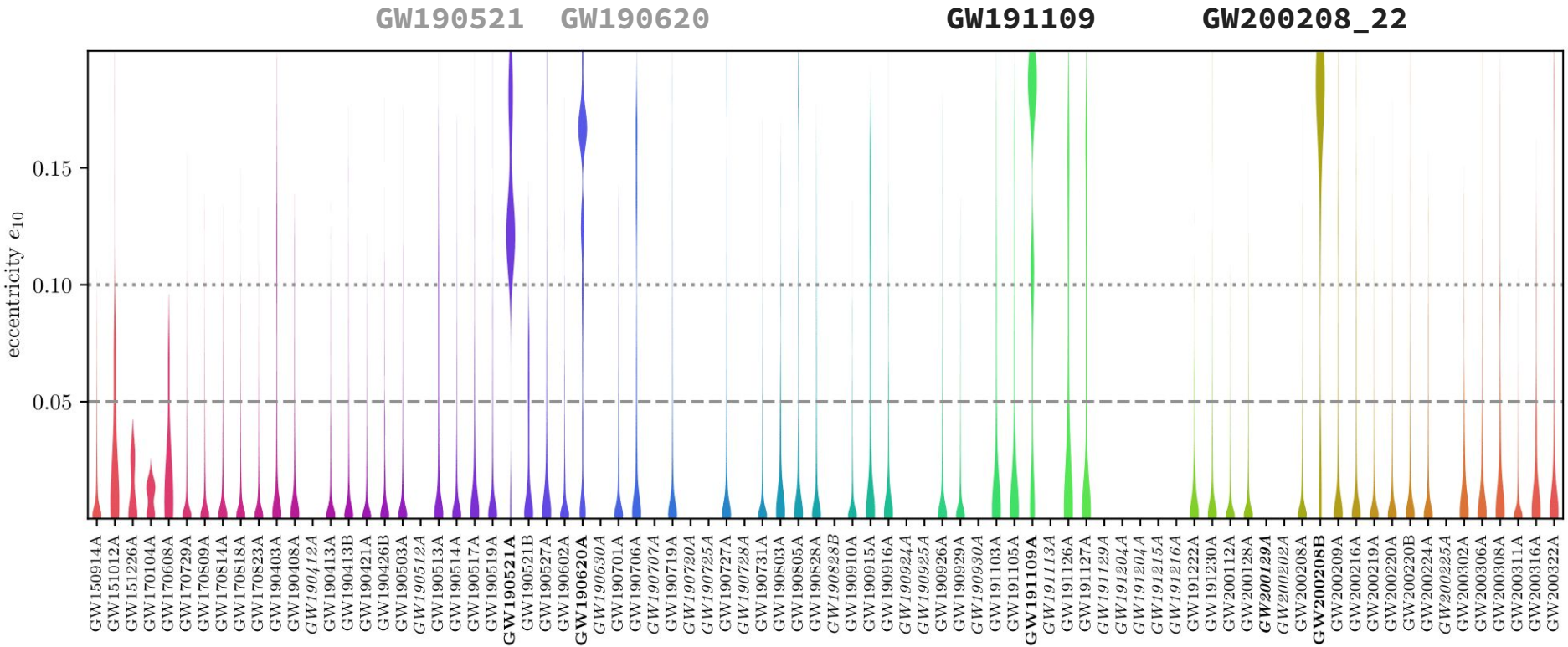


Expect ~4% of mergers above the dashed line if all mergers are from GCs (Zevin, RS, Kremer, Thrane & Lasky 2021, arXiv:2106.09042)

See also predictions from simulations of Samsing, Rodriguez, Kremer etc.

RS, Lasky & Thrane 2019, 2021
See also RS, Lasky, Thrane & Calderon-Bustillo 2020

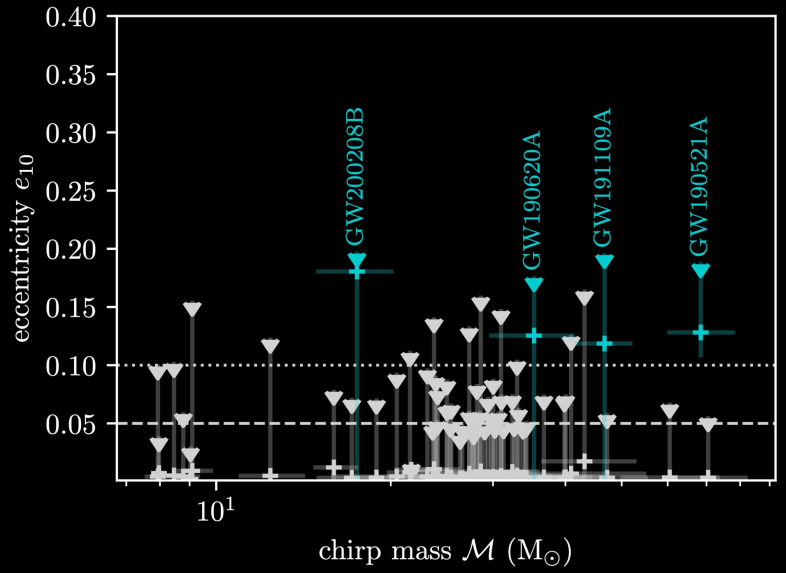
Results: GWTC-3

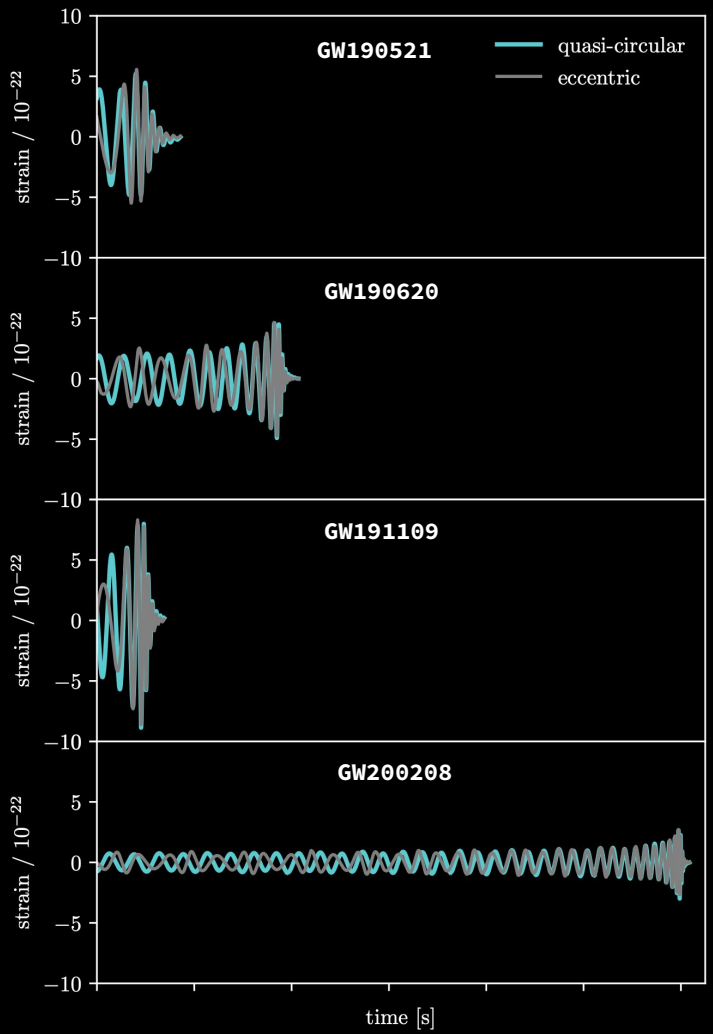


RS, Lasky & Thrane 2022, in prep.

Four (possibly) eccentric events in GWTC-3

- Panel width spans 0.35 seconds and shows median posterior waveforms





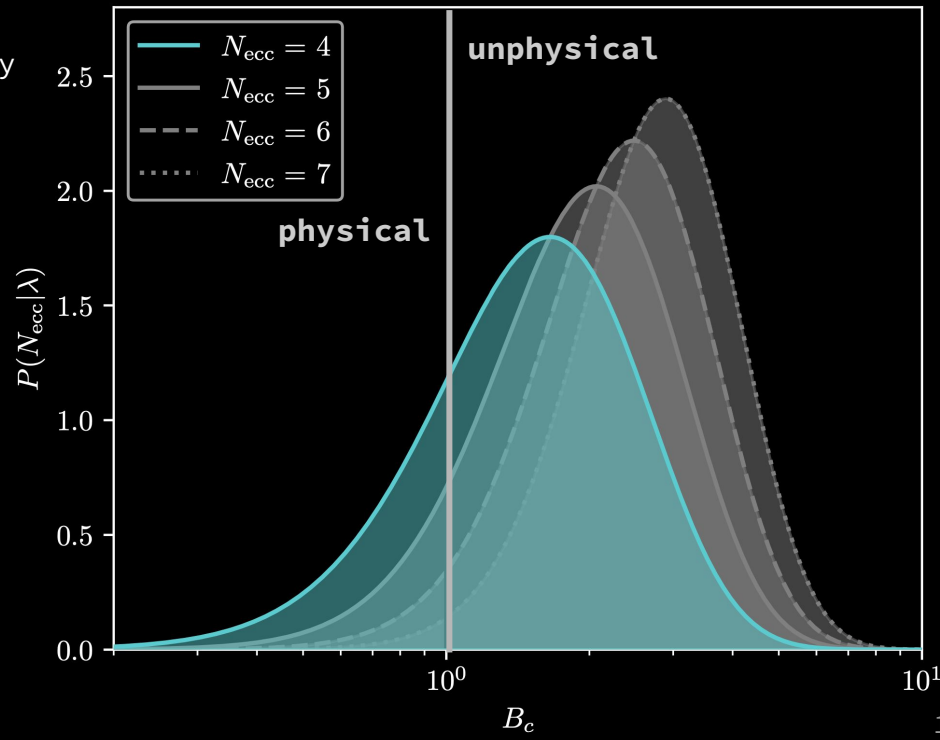
RS, Lasky & Thrane 2022, in prep.

Population implications

- Branching fraction
  - See Zevin, RS, Kremer, Thrane & Lasky 2021, arXiv:2106.09042
  - Consistent with 100% (Bc=1) of population formed in GCs
  - …but also consistent with other dynamical channels contributing eccentric mergers

$$p(N_{\rm ecc}|\lambda) = e^{-\lambda}\lambda^{N_{\rm ecc}}/N_{\rm ecc}!$$

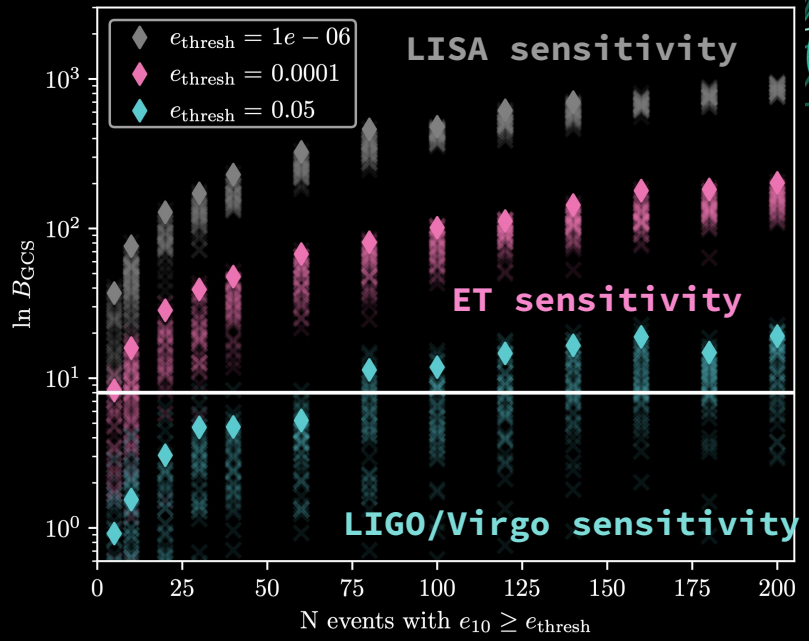
$$\lambda \equiv \xi_{\rm ecc}\beta_{\rm c}N_{\rm obs}$$



RS, Lasky & Thrane 2022, in prep.

When will we know where eccentric BBH form?

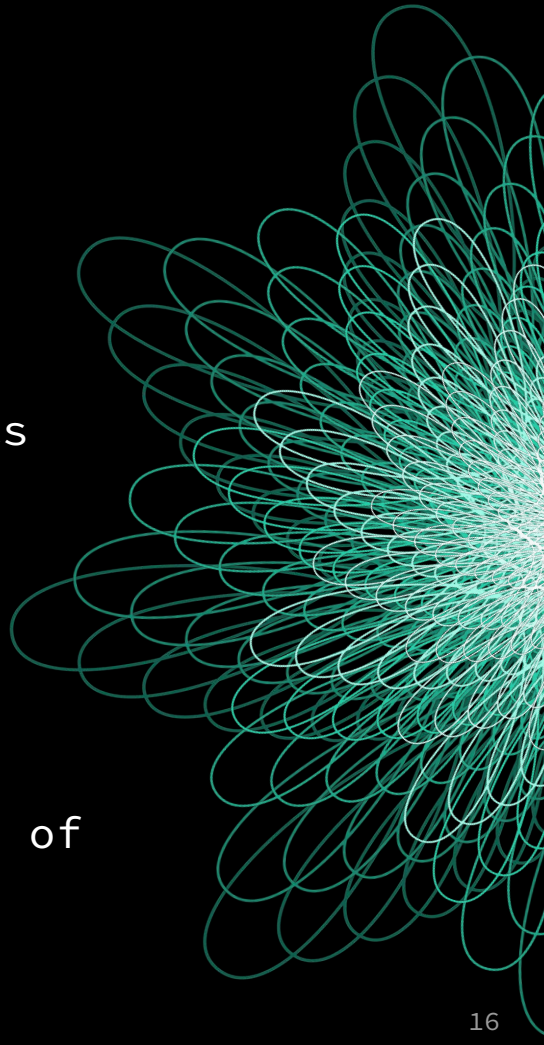
- Simulate eccentricity measurements of dynamically-formed binaries
- Compare hypotheses: GCs or AGN?
- If all form in GCs, can distinguish from AGN after ~80 detectably-eccentric LIGO-Virgo observations



RS, Lasky & Thrane 2022, in prep.

Summary

- Potentially (at least) 4 eccentric events in GWTC-3
- Consistent with 100% of mergers forming in GCs
- May imply other dynamical channels required
- Need ~80 eccentric events to distinguish dominant dynamical channel with LIGO/Virgo
- Further reading: How can we use a population of GC mergers to infer how GCs form?
  - See Romero-Shaw, Kremer, Lasky, Thrane & Samsing 2021 arXiv:011.14541



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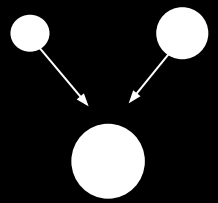
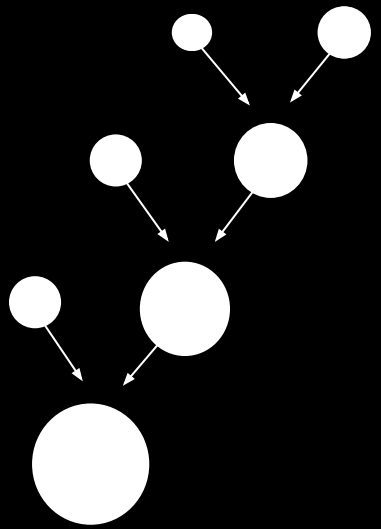


component masses ≳ 60 M⊙



component masses ~ any

Distinguishing features of formation channels

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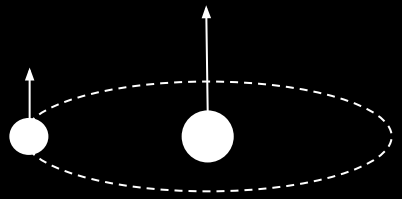
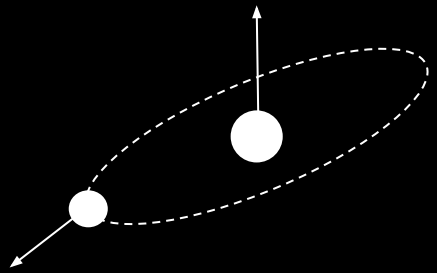


spins approximately aligned

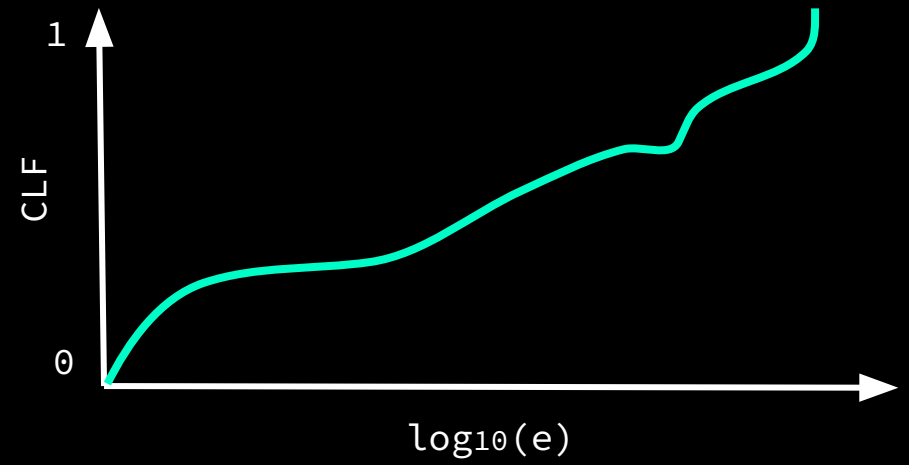


spins likely misaligned

Reconstructing eccentricity distribution

For each sample **i** with parameters **θ_i**:

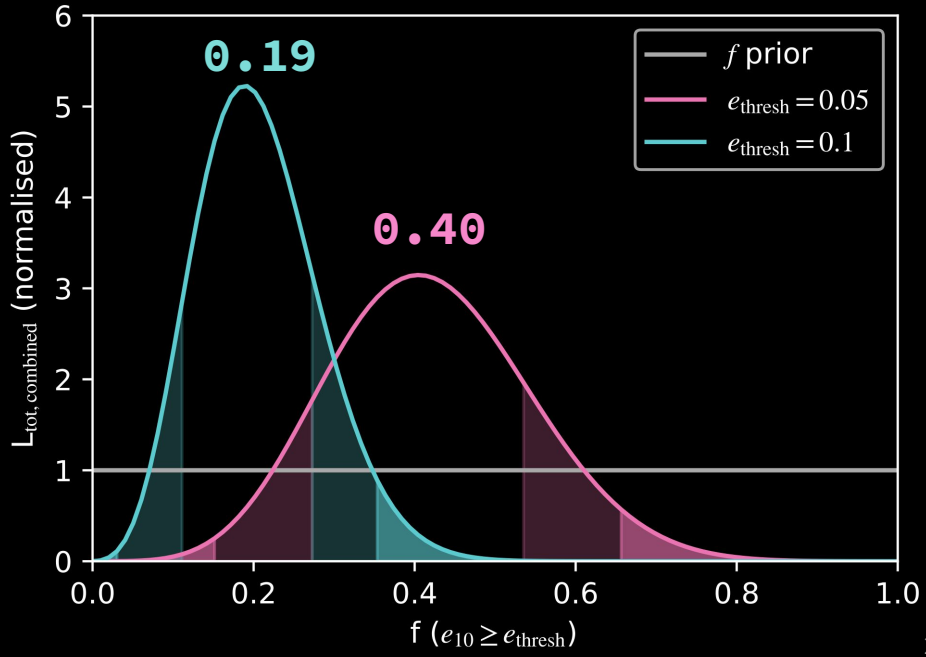
- Calculate **$L(d|e)_i$** over log-uniform grid of **e**
- Draw random sample from cumulative **$L(d|e)_i$** grid



Population implications

- Fraction of population with support for eccentricity above some threshold
- 1-, 2- and 3-sigma intervals shown
- Exclude f = 0 at greater than 2-sigma

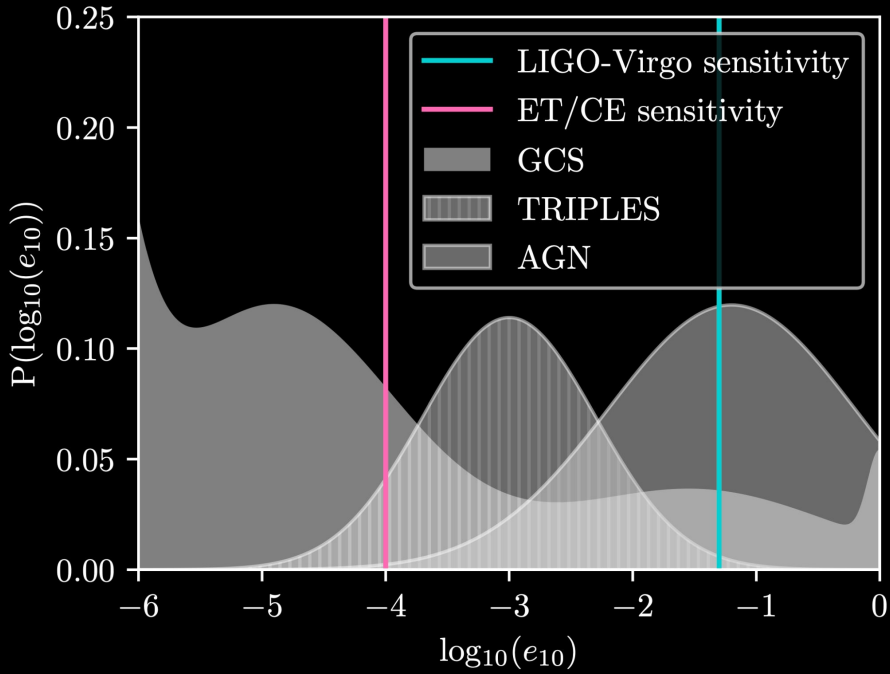
$$\mathcal{L}(d|f) = \prod_k \left(f \int_{e_{\rm thresh}}^{e_{\rm max}} de\, \pi(e) \mathcal{L}(d_k|e) + (1-f) \int_{e_{\rm min}}^{e_{\rm thresh}} de\, \pi(e) \mathcal{L}(d_k|e) \right)$$

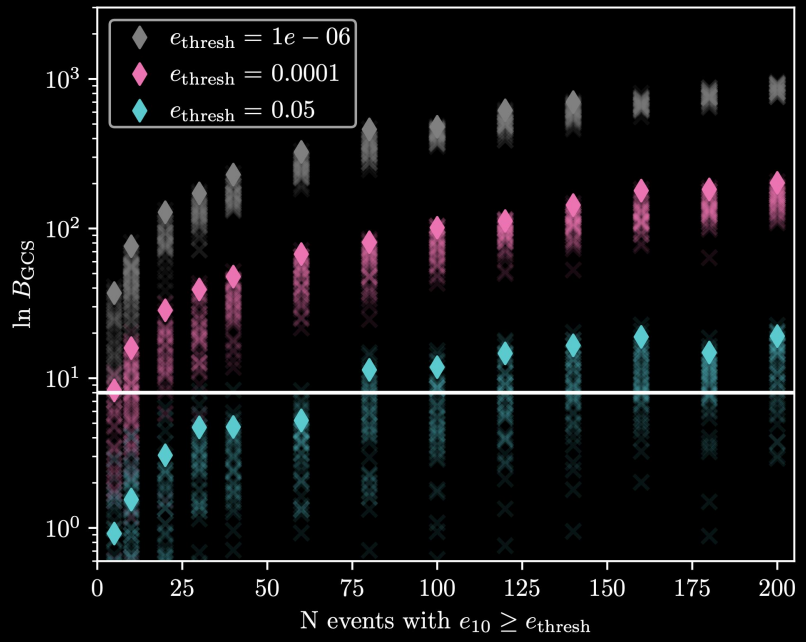


Romero-Shaw, Lasky & Thrane 2022, in prep.

When will we know where eccentric BBH form?

- Approximate each event posterior as a delta function
- Model population from GCs, compare against AGN hypothesis





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